In-Situ Plasma Cleaning of Collector Optics

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- **Introduction**
- **Sn Deposition**
- **Hydrogen Cleaning Process**
- **Experimental Setup**
- **Results and Discussion**
- **Conclusion**

Introduction

- EUV plasmas expel high-energy Sn ions and neutrals.
- Current buffer gas mitigation may not be sufficient as we progress towards high power EUV sources.
- Just a couple nanometers of Sn will significantly degrade reflectivity.
- Solution: Hydrogen Plasma Cleaning. $Sn + 4H \rightarrow SnH_4$ (g)
- SnH_4 can dissociate and re-deposit. Redeposition becomes worse with larger samples.
- Previously, an etching recipe was optimized for small samples.
- The ability to etch large surfaces will be explored, as will the effects of the etching plasma upon the substrate surface.

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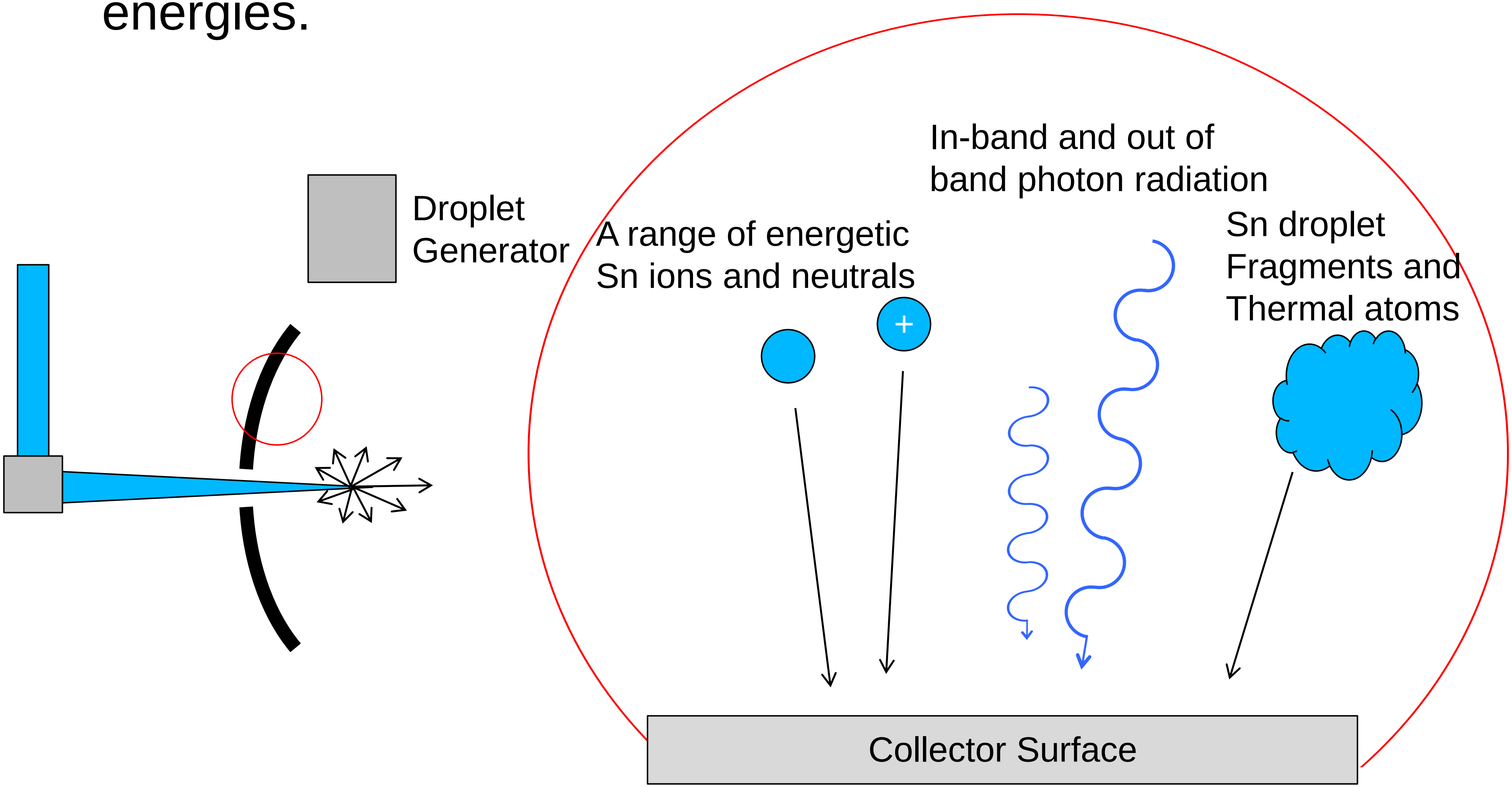
Sn Deposition in EUV Systems

- Sn droplet is blasted by laser to make EUV light (Sn^{+8}–Sn^{+12})
- Sn ions, neutrals (vapor), and particles are expelled with high energies.



Problems with Current Mitigation

👍 H_2 buffer gas slows down energetic Sn ions and neutrals.

👎 Does not fully eradicate Sn deposition.

👍 Out-of-band (~110nm) photons can dissociate H_2 into radicals.

👎 Many radicals created near plasma are blown away from collector by buffer gas flow.

👍 Secondary photoelectrons from collector surface could generate radicals at the collector (if they have enough energy). These are the “useful” radicals that can react with Sn on the collector surface.

👎 Cleaning effectiveness depends on radical production, Sn contamination, and SnH_4 removal rate.

👎 More debris may be generated in high-power EUV sources.

👎 Future balance between radical formation, etching, SnH_4 removal, and re-deposition could change with higher EUV power.

- Net deposition still occurs.
- Collector optics must undergo cleaning process other than relying on radicals produced in existing mitigation scheme.
- Best scenario: Perform cleaning *in the chamber* with minimal downtime.

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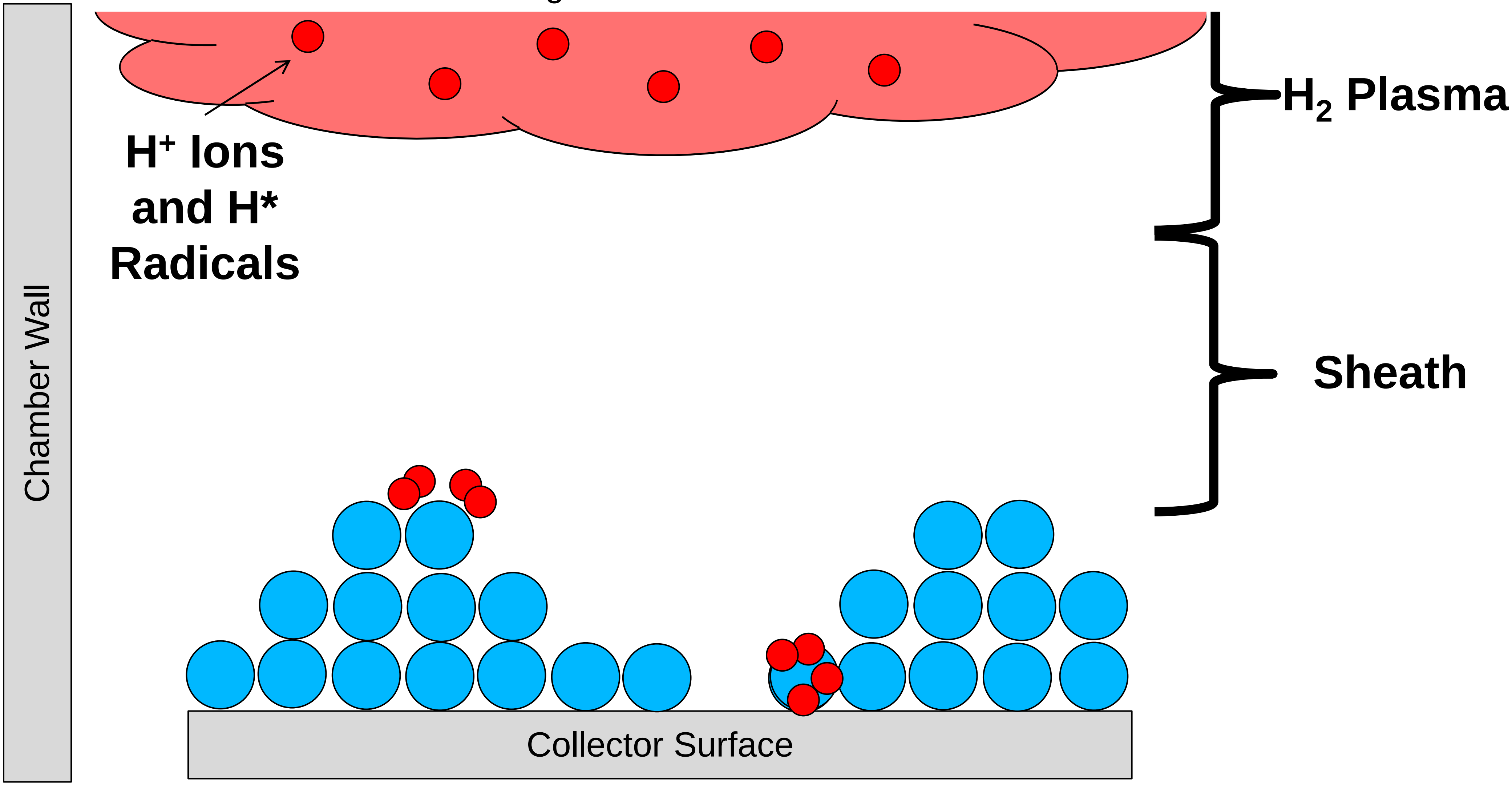
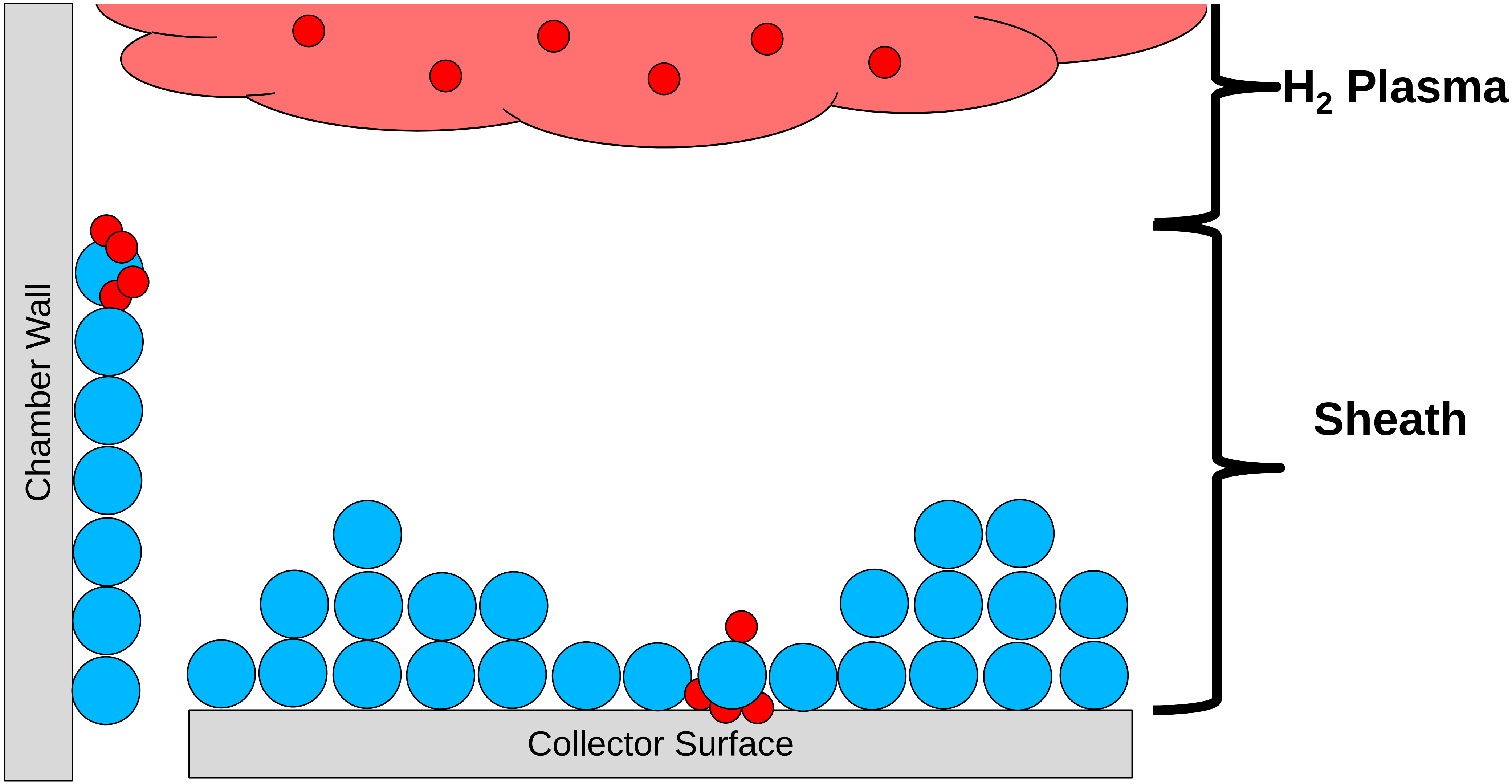
How Hydrogen Plasma Cleans

- Surface adsorption and diffusion occurs until SnH_4 is formed.
- Volatile SnH_4 either gets pumped out, or ... the fragile SnH_4 decomposes on a surface (wall or substrate).
- H^+ ions are accelerated through the sheath and H* radicals diffuse toward the surface.



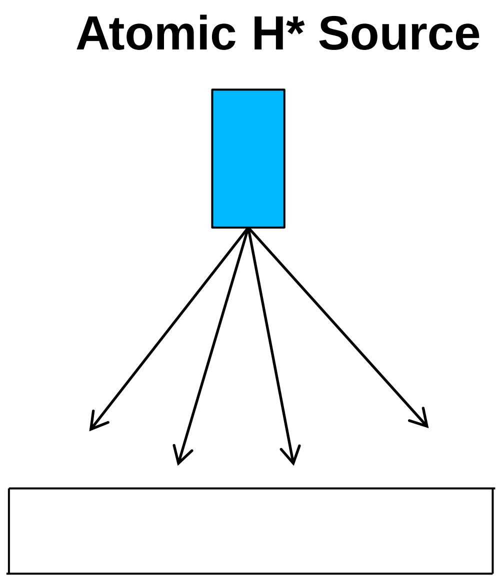
Redeposition

- This Sn can be redeposited on the collector.
- SnH_4 can deposit Sn on chamber surfaces.

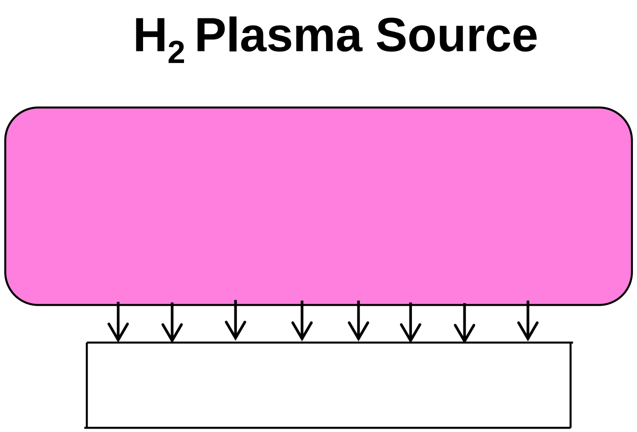


Hydrogen Plasma Vs. Atomic Hydrogen Source

- Atomic Hydrogen Source: External Point Source
  - $1/r^2$ flux drop off
  - Relies on long distance diffusion
  - Diffusion can go against the inflow of hydrogen
  - Recombination can occur when radicals hit walls on their way to the collector



- Hydrogen Plasma: Internal Radical Source
  - Radicals created close to Sn
  - Decreased reliance on diffusion
  - Can make use of H_2 buffer gas flow already in the chamber



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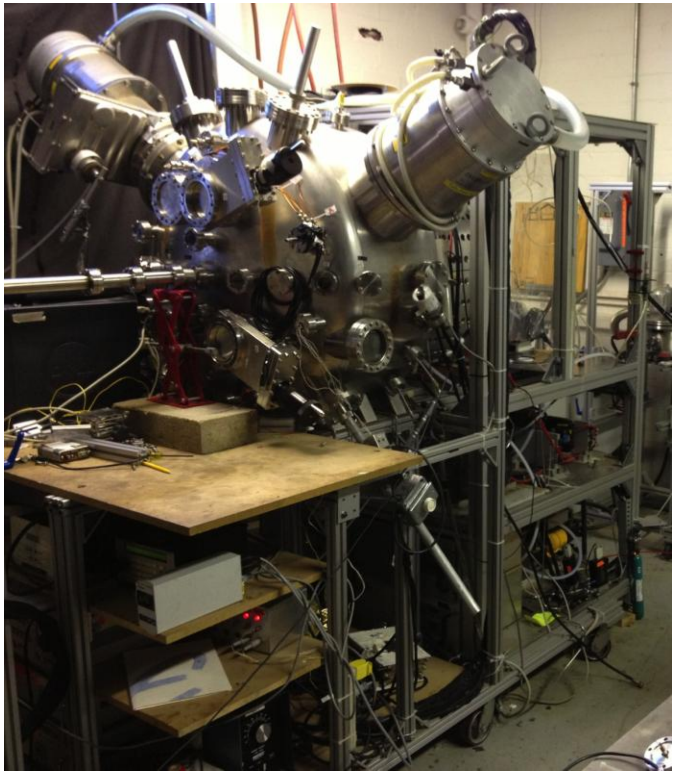
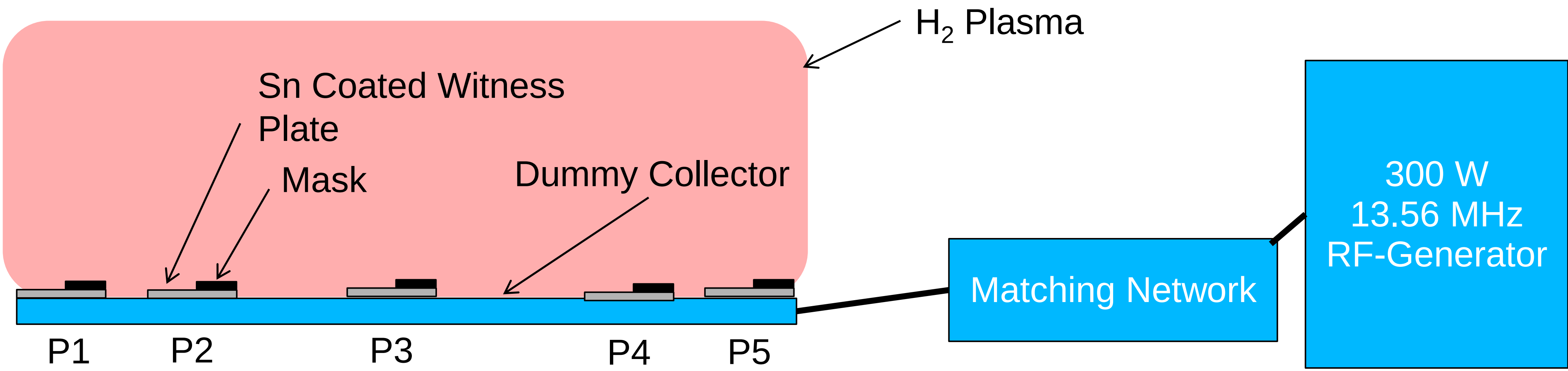
Experimental Apparatus

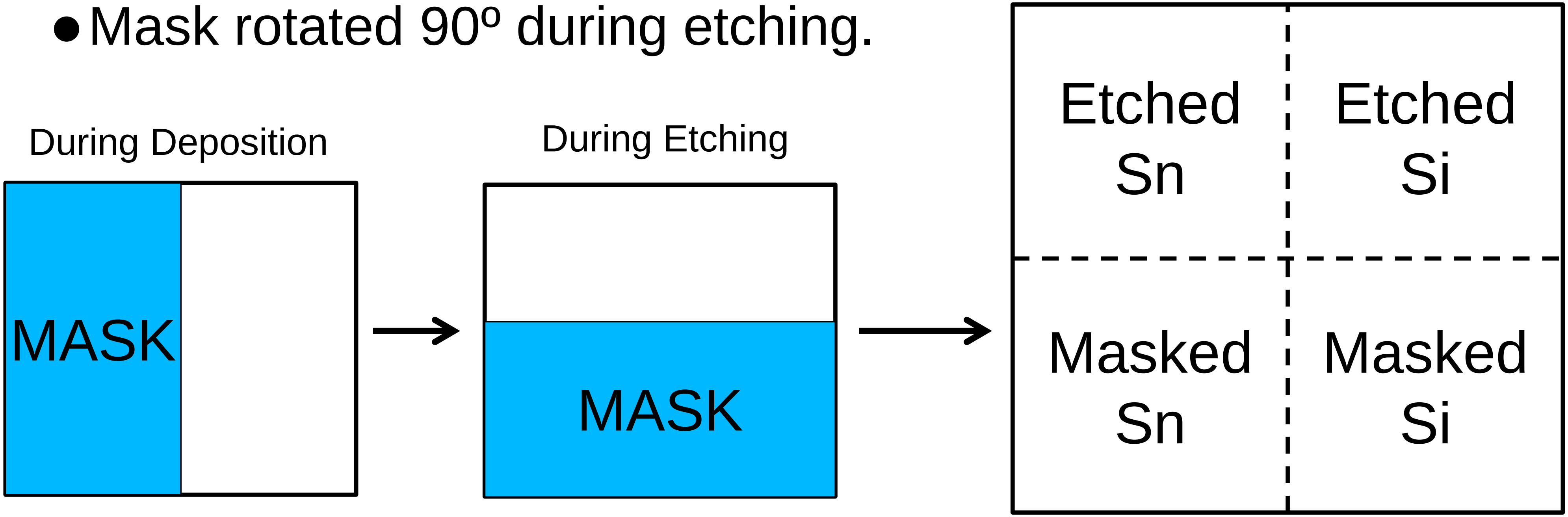
- 5 Masked Samples are placed on 790 cm^2 steel dummy collector.
- Magnetron sputtering used to coat entire dummy collector with thicknesses of 20, 50, 100, and 200nm (varying by experiment).
- Collector installed in CPMI's XTS 13-35 source chamber.
- 300W supply run for 2 hrs.





Sample Masking Procedure

- Si samples (approx. 1 cm^2)placed on dummy collector to enable measurement in characterization machines.
- Half-sample masked for deposition.
- Mask rotated 90º during etching.



Etched Sn: Deposited with Sn, Exposed during Etching
Masked Sn: Deposited with Sn, Exposed during Etching

Etched Si: Masked during Deposition, Exposed during Etching
Masked Si: Masked during Deposition, Masked during Etching

Experiment Design

- Goal: Maximum **REMOVAL** rate.
- Key Question: Can we successfully etch the entire 790cm^2 dummy collector?
- Dummy collector attached to a 13.56 MHz, 300 W RF supply.
- Etch Time: 2 hrs
- Previous Experiments → Optimum Parameters for Our Setup: 500sccm, 130mTorr
- Higher pressures lead to more radicals but also more dissociating collisions for SnH_4.
- Higher flow rates blow SnH_4 away more easily but also blow away radicals.
- For higher, industrial-level pressures, compensation could be achieved with industrial-level flow rates.

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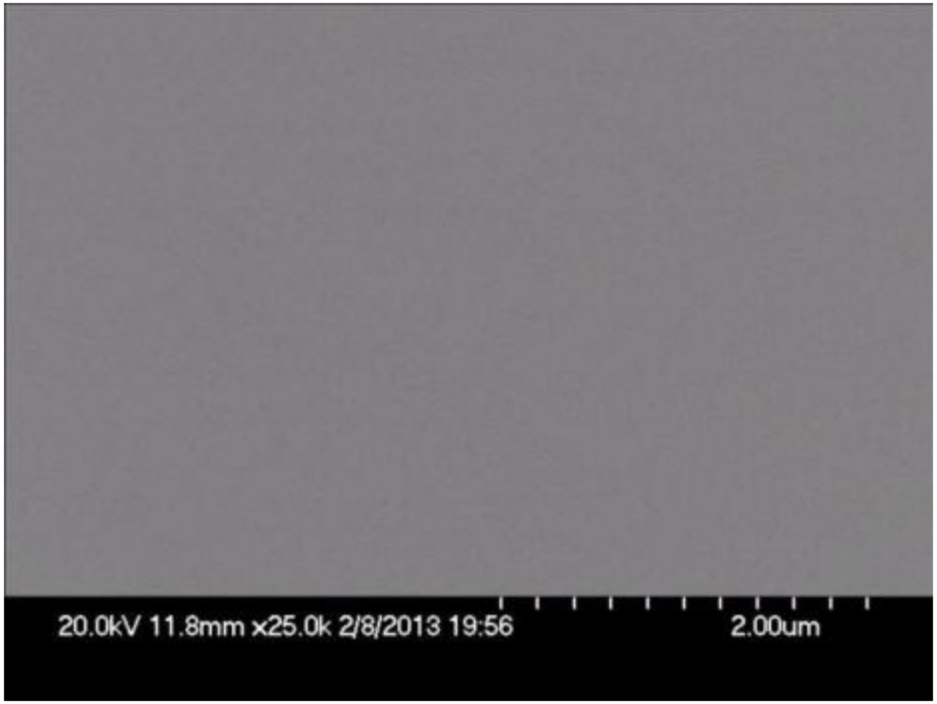
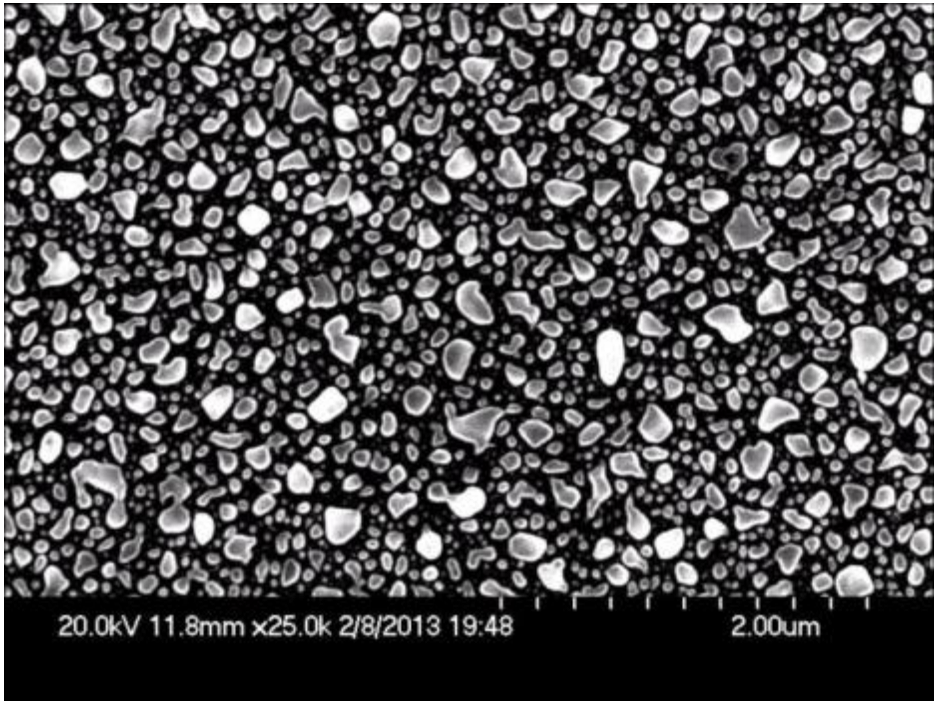
20nm Etch

- 20nm Deposited via Magnetron Sputtering. Etched for 2 hours.
- Profilometry on all samples indicated complete etch.
- SEM Images showed distinct contrast between Etched Sn and Masked Sn quadrants. Etched Sn quadrant appeared pristine.

Etched Sn

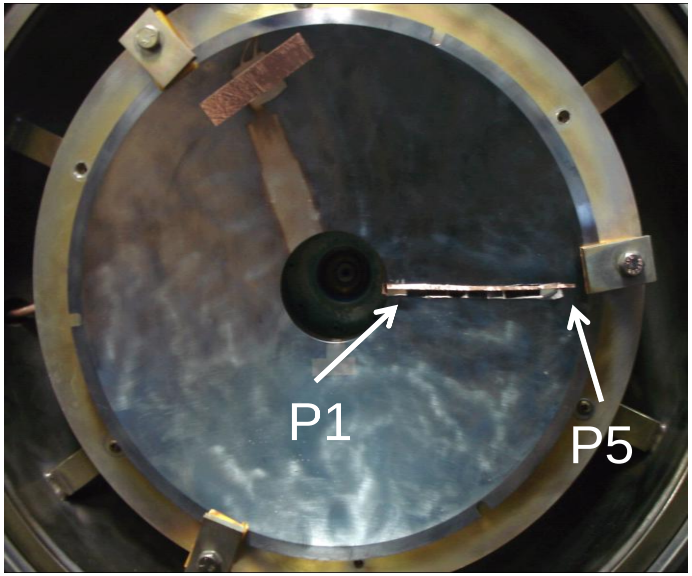


Masked Sn

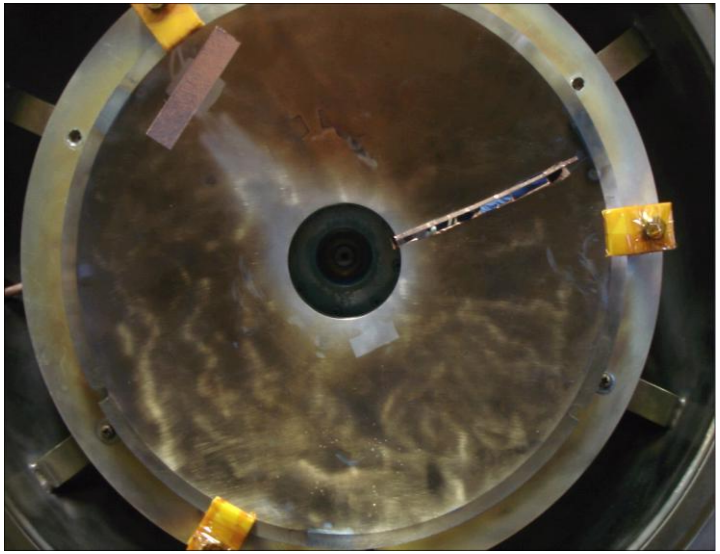


Dummy Collector Images

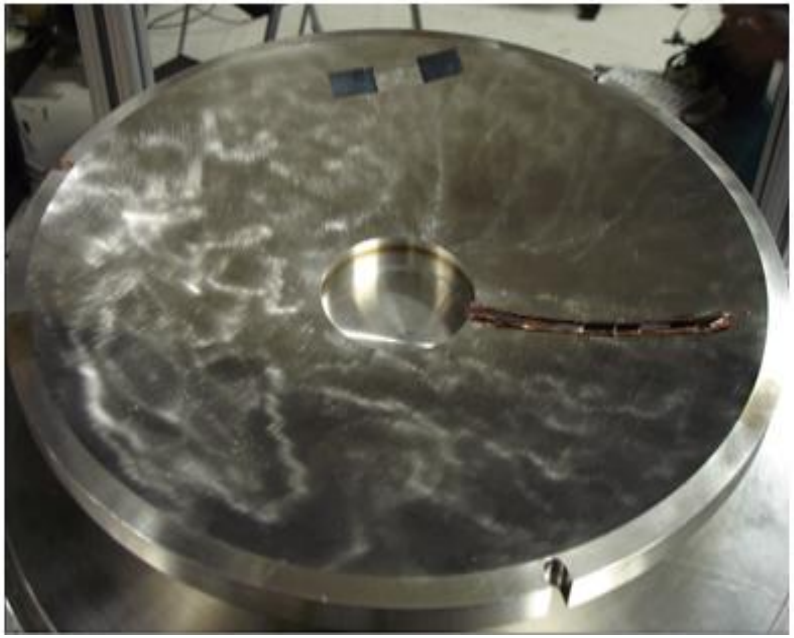
Before Etching



4 min Etching



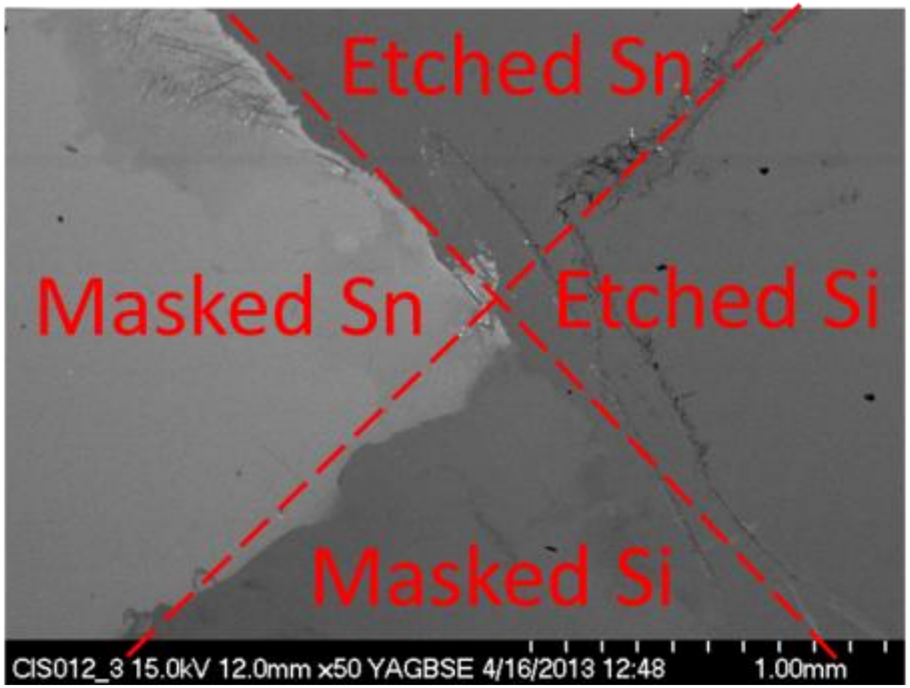
After Etching



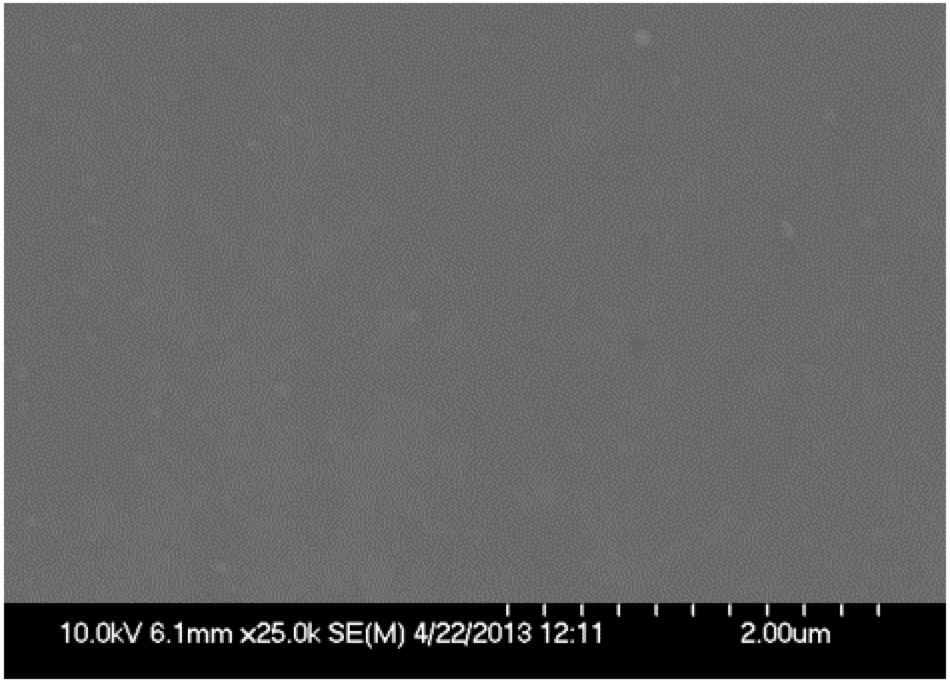
50nm Etch

- 50nm Deposited via Magnetron Sputtering. Etched for 2 hours.
- Profilometry of all samples indicated complete etch.
- SEM Backscattered Electron Detector (BSE) detects surface material composition; indicated complete etch.
- Normal SEM image (secondary electron image) of Etched Sn quadrant was clean.
- No noticeable step between Etched Si and Masked Si.

BSE Image of 4 quadrants

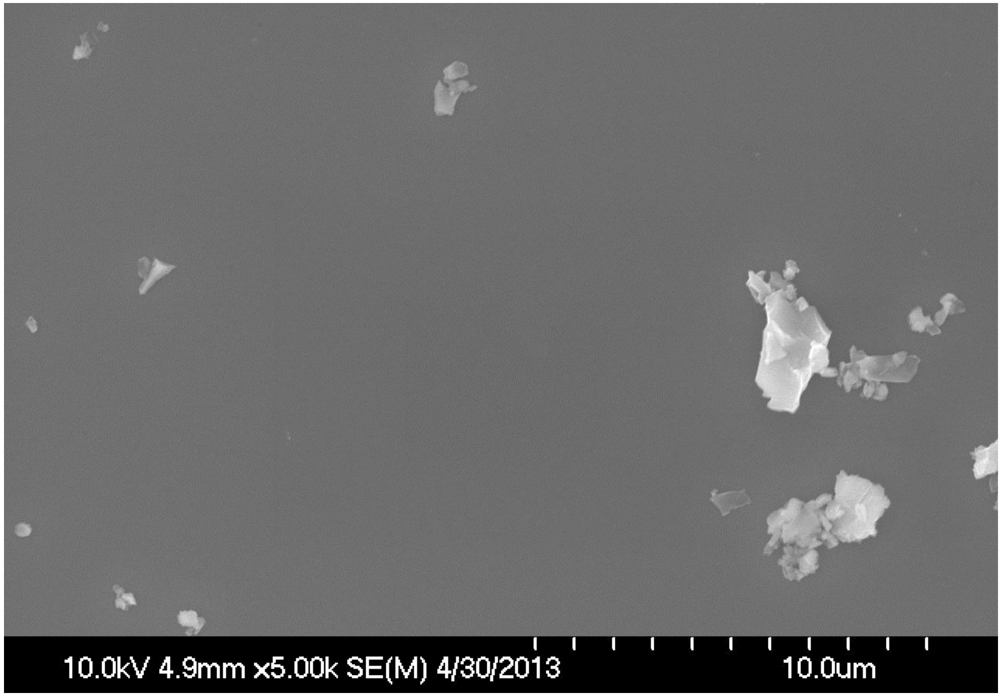


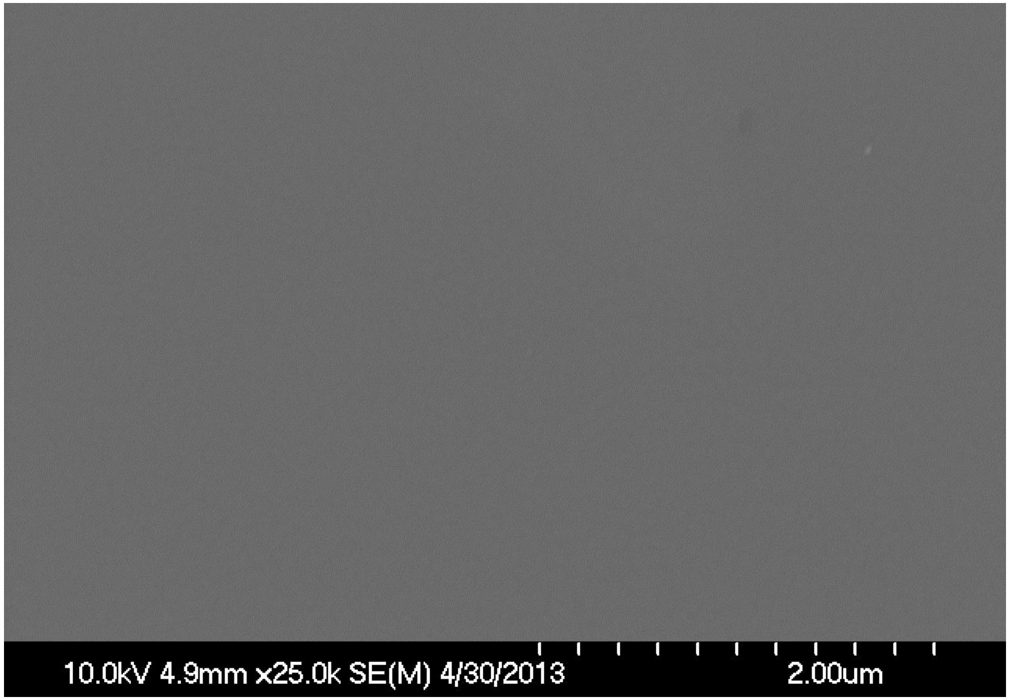
SEI Image of Etched Sn



100nm Etch

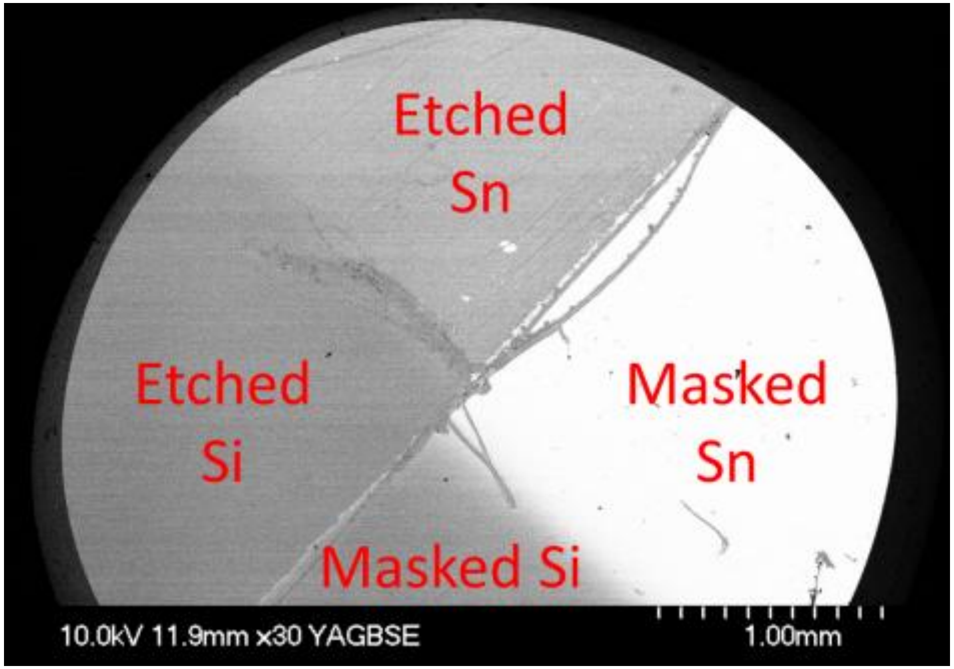
- 100nm Deposited via Magnetron Sputtering. Etched for 2 hours.
- Profilometry of all samples indicated etch at or near completion (within ~10nm error bars). BSE Image also appeared to show etch again.
- Zoomed-out SEI images show some islands of Sn, indicating that the 2-hour etch was nearing its limits at 100nm (Sample 3 shown below).

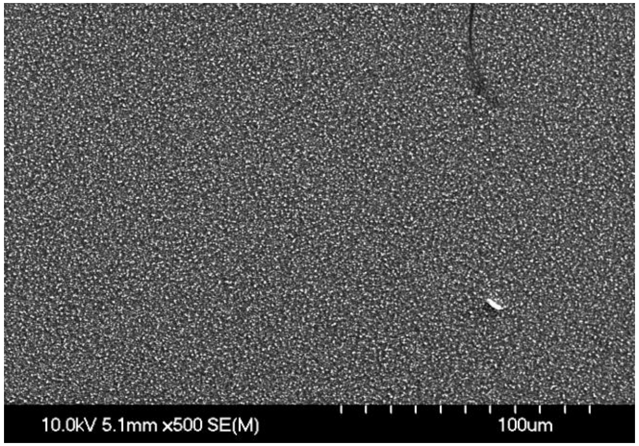




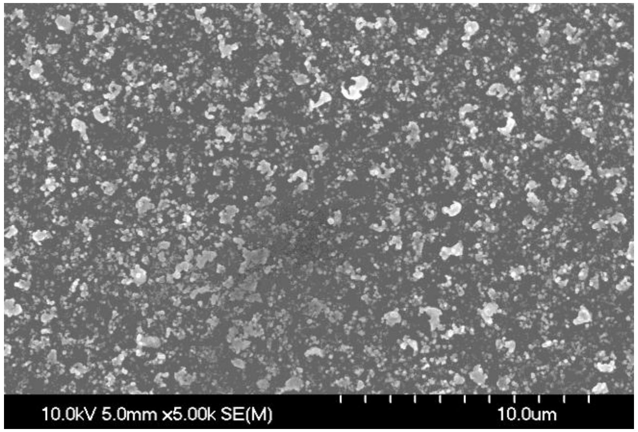
200nm Etch

- 200nm Deposited via Magnetron Sputtering. Etched for 2 hours.
- Visual inspection and profilometry indicated incomplete etching.
- BSE image of Sample 3 confirmed incomplete etching (Etched Sn color not identical to Etched Si color).
- SEI Images show Sn islands all over the Etched Sn quadrant.

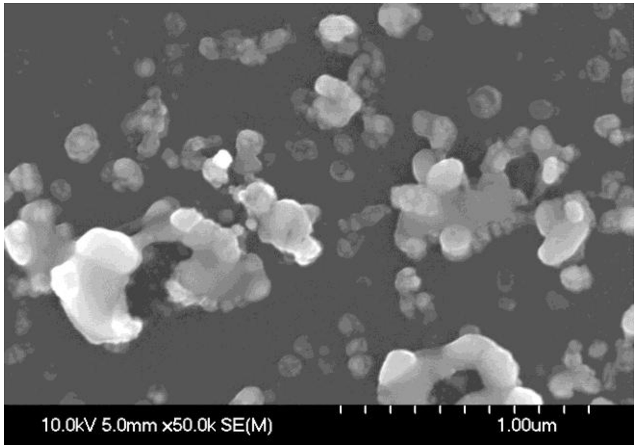




500x



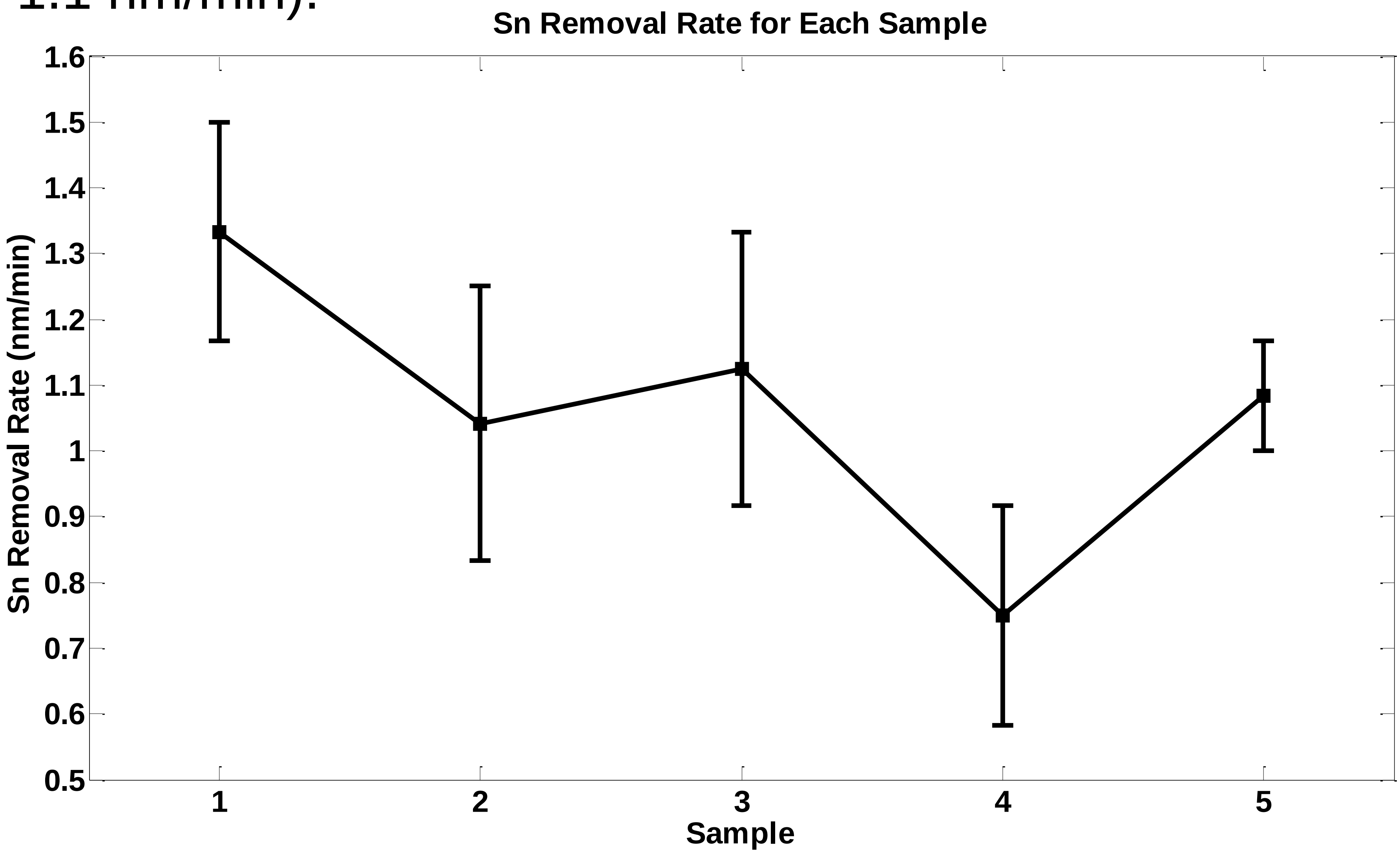
5kx



50kx

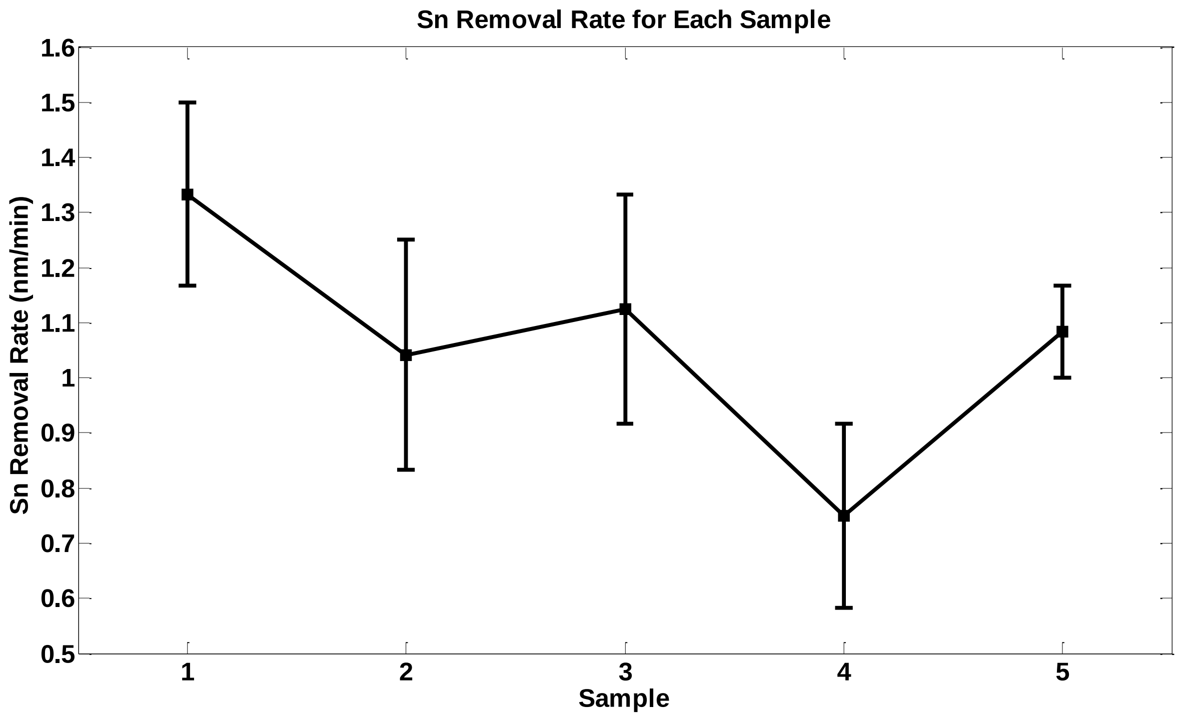
Removal Rate

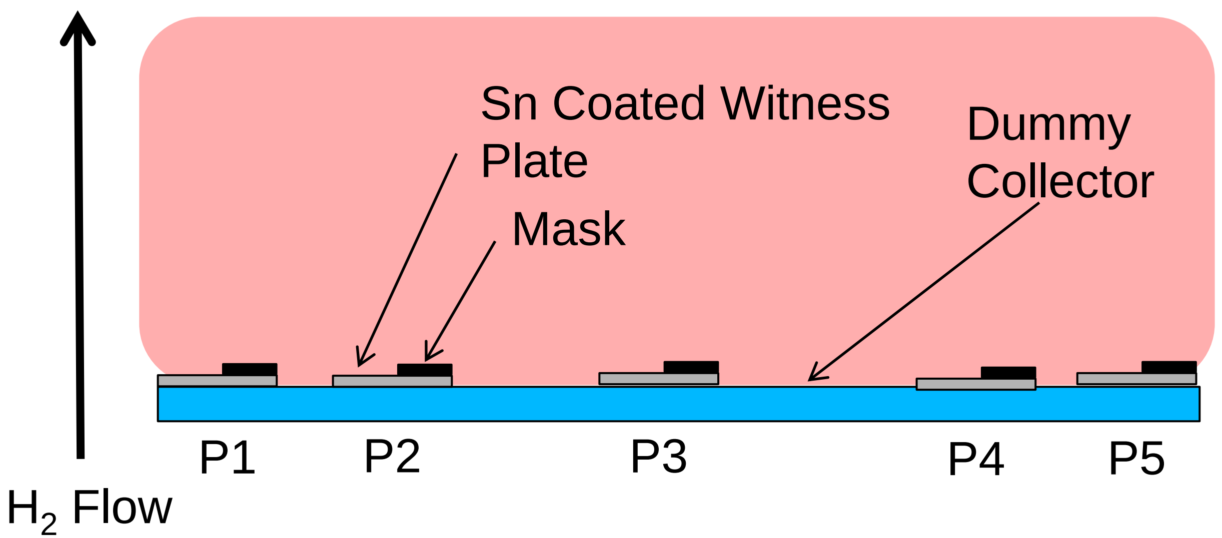
- Sn thickness measured with profilometer to determine removal rate from 200nm experiment (average approximately 1.1 nm/min).



Removal Rate Variation

- Removal Rate varies by position.
- Dependent on radical density and ability to remove SnH_4.
- Samples 1 and 5 are close to edges of dummy collector. Less surrounding Sn, and etched SnH_4 can enter voids to be removed.
- Higher local electric fields at edges → More radicals
- Geometry causes Sample 1 to see the highest flow rate.

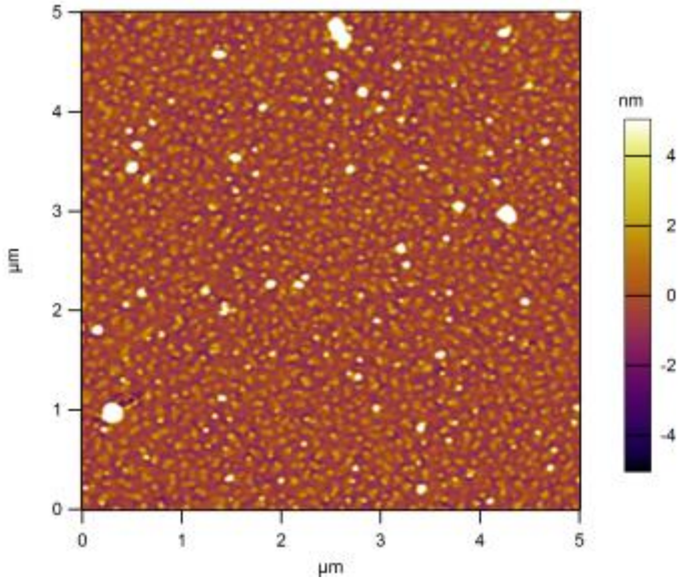




AFM: Completing the Picture

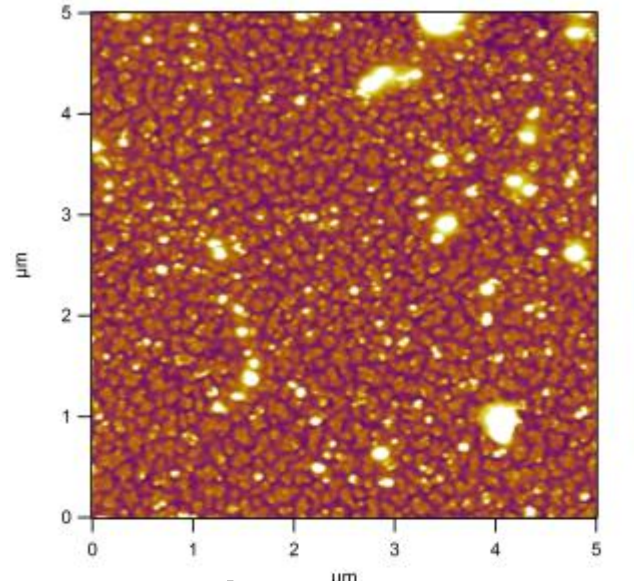
- AFM can measure RMS roughness.
- Roughness can be caused by sample handling, dirt in the air, remaining Sn islands, and sputtering. Digital “mask” eliminates some obvious contaminants from the calculation.
- Scan Size: 5µm x 5µm (Sample 3 Examples Shown Below)

50nm Etched Sn



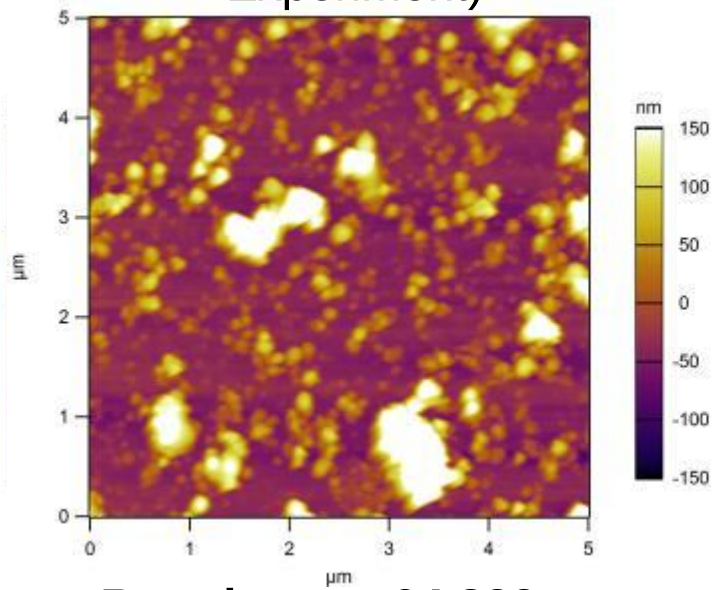
Roughness: 0.882nm

100nm Etched Sn



Roughness: 2.213nm

Incomplete Etch (from 200nm Experiment)



Roughness: 64.832nm

The 200nm sample roughness is extremely close to the Sn thickness measured by the profilometer (65nm). This helps validate the profilometer data.

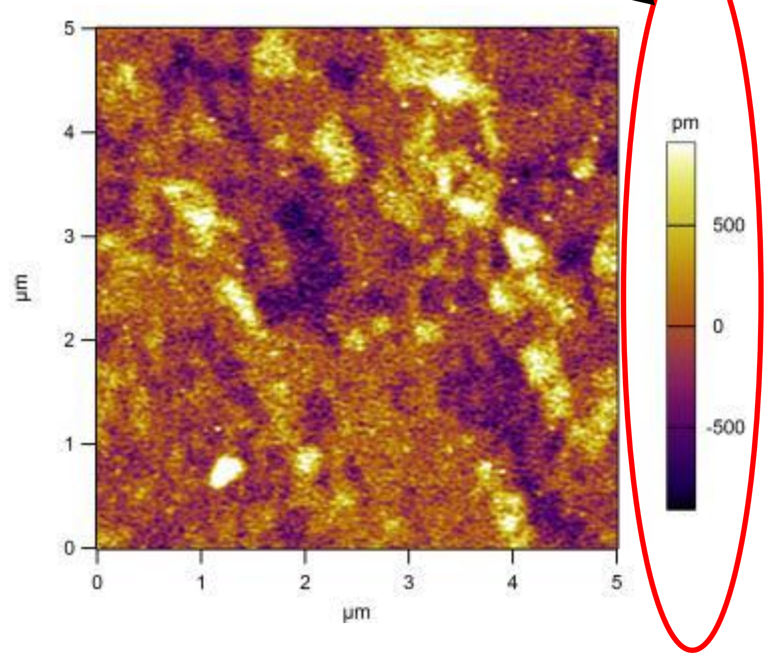
What the AFM Tells Us

- Though profilometry and etch rates indicate that “full etching” should be observed in the 50nm and 100nm samples, SEM and AFM show that there are some small Sn islands left.
- These are much smaller than the Sn chunks observed everywhere on the incompletely-etched 200nm sample.
- As etching reduces surface coverage and islands get smaller, it becomes harder for H radicals to find the few remaining islands of Sn.
- Fully removing all Sn islands remains a challenge and the subject of ongoing research. What matters most is having a low surface coverage.

Sputtering?

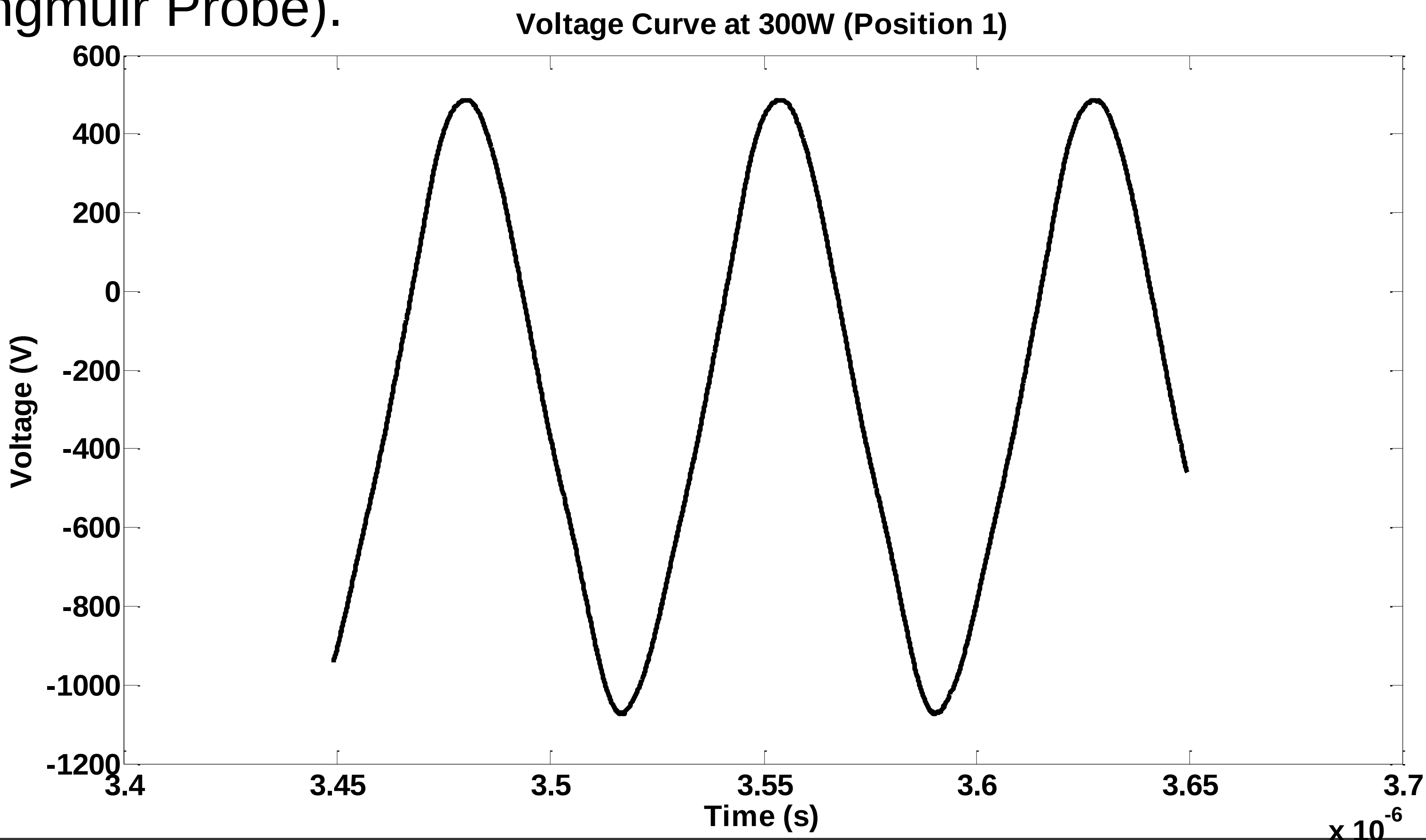
- Does this technique cause sputtering of the substrate?
- During profilometry, no noticeable difference between Etch Si and Mask Si
- “Etch Si” quadrant examined under AFM (Sample 5, 200nm experiment)
- Roughness: 0.322nm
- On order of expected roughness for polished wafer (~0.15nm)
- Though they do not rule out small amounts of sputtering, these results do not show evidence of sputtering.
- Application of etching technique to actual MLM samples is next logical step.

Note picometer scale



Voltage Curve on Dummy Collector

- Shows self-biasing associated with RF plasma sheaths (caused by Child-Langmuir current density limitation). Will this cause sputtering on a real MLM?
- Average Value = DC bias ~= 300V. V_{plasma} ~= 50V (measured with Langmuir Probe).



SRIM Simulations

- Sputtering Yields calculated with SRIM.
- Used to estimate sputtering rates.

$$Ion\ Flux = \Gamma = n_e v_i \qquad Sputtering\ Rate = \Gamma\ x\ Yield\ x \frac{1}{density}$$

350 eV Ions

	Si	**Mo**	**Ru**
Sputtering Yield	0.0207 at/ion	0	0
Sputtering Rate	0.036 nm/min	0	0
Thickness Sputtered after 2 hours	4.38 nm	0	0

1050 eV Ions

	Si	**Mo**	**Ru**
Sputtering Yield	0.0208 at/ion	0.0076 at/ion	0.0089 at/ion
Sputtering Rate	0.064 nm/min	0.0097 nm/min	0.0097 nm/min
Thickness Sputtered after 2 hours	7.62 nm	1.17 nm	1.16 nm

- These thicknesses are all within the error bars of the profilometer. Careful study of actual MLM samples is warranted.
- Sn etching is about 17x faster than 1050eV simulated Si sputtering.

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Conclusions

- Dissociation of SnH_4 does not prohibit Sn removal from a 790 cm^2 dummy collector by an in-situ H_2 plasma cleaning system.
- Removal rates of approximately 1.1 nm/min have been observed in laboratory experiments with 300W RF, 500sccm, and 130mTorr. Rates would likely increase with industrial-scale flow and RF power.
- Roughness seemingly caused by the technique is likely due to the presence of small remaining Sn islands. Full elimination of all Sn islands is a subject of ongoing and future research.
- Sputtering of the actual sample surface seems minimal, though further tests on actual MLM samples will be instructive. The actual amount of etch time could be the key to minimizing damage from sputtering.
- An end-detection method (in progress) could also alleviate any concerns of accidentally harming the substrate.

Acknowledgments

- Special thanks to Cymer for funding this research.
- Special thanks to Intel, inc., SEMATECH, inc., and Xtreme Technologies, GmBH for providing the XTS 13-35 source.
- Part of this work was carried out in part in the Frederick Seitz Materials Research Laboratory Central Facilities, University of Illinois, which is partially supported by the U.S. Department of Energy under grants DEFG02-07ER46453 and DE-FG02-07ER46471.
- Thanks to undergraduate assistants Louis Chapdelaine, Pawel Piotrowicz, and Gianluca Panici.

Thank You For Your Attention!